Effect of Serial PMSs on Operational Benefits of Arrival Flights

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Abstract: In order to alleviate the flight congestion in terminal areas (TMAs), it is of great significance to develop an effective method. An arrival sequencing model based on the serial point merge systems (PMSs) is constructed to improve the operational benefits of arrival flights. The approach of first come first service (FCFS) combined with the method of constraint position shift (CPS) is used as the sequencing strategy. Through the simulated annealing algorithm, the results show that the arrival flights sequencing through serial PMSs has significant advantages in reducing delays and increasing runway throughput especially in the case of high traffic loads. The proposed approach is conducive in promoting the implementation and application of serial PMS.

Key words: serial point merge systems(PMSs); terminal area(TMA); arrival flights; operational benefits

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0 Introduction

Nowadays, most terminal areas (TMAs) adopt the method of radar vectoring to control arrival flights, which is very flexible. However, in the case of high traffic loads, the workload on air traffic controllers has increased significantly and instructions such as flying around and circling appear, make the flying time of the flights in TMAs longer. This reduces the economic benefits of flights, and increases pollutant emissions. In order to overcome the disadvantages of the traditional arrival procedures in operation, point merge systems (PMSs) came into being.

A PMS[1-2] is a new type of flight procedure based on precision area navigation[3] (P-RNAV), proposed by the experimental center of EUROCONTROL. For the flights flying on PMSs, the trajectory can be stretched as needed, and many studies have verified its effectiveness in reducing the delay, the flight cost, the workload on controllers and pollutant emissions. Ivanescu et al.[4] compared radar vectoring and PMSs, and the results showed that PMSs had significant advantages in reducing the number of instructions and pollutant emissions. Favennec et al.[5] showed a typical TMA configuration of the PMS. Meric et al.[6] designed a PMS for the convergence runway of Istanbul Ataturk International Airport. Liang et al.[7-8] proposed a method to use a PMS to sequence the arrival flights, and evaluated the benefits of a PMS from the aspects of flight efficiency and runway throughput. They also proposed a multi-layer PMS which can reduce the delay of multiple parallel runways at the same time[9]. Hong et al.[10] proposed a scheduling algorithm based on mixed integer linear programming (MILP) and optimized it. Lee et al.[11] evaluated the operational benefits of PMSs in TMAs with multi-airports. Sahin et al.[12] proposed a PMS optimization sequencing algorithm that includes waiting programs.

These scholars mostly focused on the advantages of a single PMS in terms of flight control, delays in TMAs, and reduction of fuel consumption. Few has conducted research on serial PMSs. As the name implies, a serial of PMSs are generally formed by linking multiple single PMSs, as is

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shown in Fig.1. Due to the limited airspace resources in TMAs, it is not realistic to connect more than two PMSs in series. Therefore, this paper studies the serial PMSs composed of two PMSs. For flight operation, there is no difference between each PMS in the serial PMSs and a single PMS. The only difference is that the linking segment of the serial PMS also allows flight operation and minor sequence adjustment.

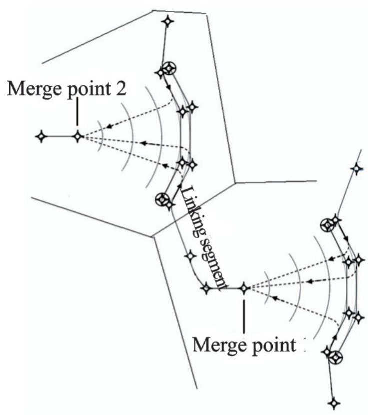

Fig.1 Basic configuration of serial PMSs

In the guidance of EUROCONTROL on PMSs, only the definition and structural analysis of the serial PMSs are introduced, and its operational benefits have not been researched yet[2]. However, during the process of actual operation in TMAs, the controller prefers to performing an initial sequence of aircraft in advance, and then performs an accurate sequence near the final to determine the landing sequence. Serial PMSs can exactly meet such needs, the PMSs close to the boundary of TMAs can be used for initial sequencing and the PMSs close to the final for accurate sequencing. In the linking segment of the two PMSs, minor adjustments of the sequence are also allowed. The Tan Son Nhat International Airport in Vietnam has used a serial of PMSs since of 2019 and has achieved good benefits. Therefore, the study of serial PMSs has important practical significance. This paper has made contributions from three aspects as follows:

(1) This paper constructes a framework of serial PMSs design method and operation mode.

(2) This paper establishes a sequencing model for arrival flights in PMSs.

(3) Guangzhou Baiyun International Airport is taken as an example, and the flights sequence is adjusted in the single PMSs and serial PMSs, to verify the operational benefits of the serial PMSs.

1 Serial PMSs Framework

1.1 Design of a serial of PMSs

The serial PMSs include at least two PMSs. The design of each PMS can refer to the range of the classic PMS element design according to specific TMAs[2]. The key to a serial of PSMs lies in its linking method.

Smaller-bigger means the arrival flights first performs an initial sequencing on the PMS with a smaller area, and then performs a minor adjustment on the PMS with a larger area. Bigger-smaller means the flights performs an initial sequencing on the PMS with a larger area, and then performs a minor adjustment on the PMS with a smaller area. Smaller-bigger is designed to consider the addition of a PMS in the busy direction on the basis of the original single PMS. When this form of PMS is used, the original PMS with a larger area will be the main place to accommodate flights approaching in various directions. In the direction where the arrival traffic is busier, the flights will be sequenced in advance through a PMS with a smaller area to alleviate the congestion in the TMA. The serial bigger-smaller PMS means that the area of the PMS that the arrival flights go through during the initial sequencing is larger, and the area of the PMS is smaller for minor adjustment. For the first PMS, its area is larger, which can facilitate the integration of the chaotic and disorderly arrival flights from different directions. The second PMS only needs to provide a minor adjustment for the flights that arrive from the same direction with an initial sequence, so the PMS can be designed to be smaller.

1.2 Operation mode

In the serial PMSs, the operation of arrival flights can be regarded as three separate parts, that is, the two single PMSs and the operation on the linking segment. Therefore, the flights operation on a single PMS is analogous to the operation of the flights on a serial of PMSs. Therefore, the following describies the operation of the flights on a single PMS. As shown in Fig. 2, there are multiple key points in PMSs, among which point M is the merge point, and point A and B are the entry points of the PMSs.

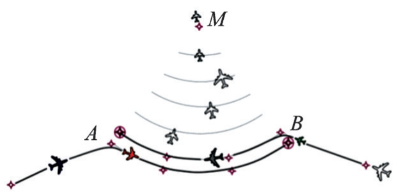

Fig.2 Operation process of flights in PMSs

In Fig.2, the orange and gray flights are flying on a sequencing leg. According to control automation equipment or decision-making recommendations, it is recommended that the controller first let the gray flight fly directly to the merge point, and then let the orange flight fly to the merge point. When the controller judges that the gray flight meets the minimum safe distance between the preceding flight, the controller can issue a "direct to" instruction to the gray flight. When the gray flight flies to a given position, the controller can issue a "direct to" instruction to the orange flight. For the flight that has received a "direct to" instruction and is flying to the merge point, the distance between them must be no less than the given separation. The controller can adjust the speed of the flight to ensure that the distance between the flight meets the requirements.

2 Approach Trajectory Optimization Model of Serial PMSs

2.1 Assumptions

The biggest advantage of PMSs is that it can adjust the landing sequence of arrival flights by sequencing legs. Many scholars have studied the method of establishing a sequencing model for a single PMS. After reaching the PMS, the arrival flight first enters the sequencing leg. On the sequencing leg, the turning sequence of flight can be adjusted according to a specific objective function. In the TMA of a single PMS, the PMS is often close to the final approach fix (FAF), thus the sequence of aircraft turning to the merge point is the final landing sequence. For the serial PMSs, the construction of the flight sequencing model is roughly similar to the combination of two PMSs. The difference is that the linking segments also allow for minor adjustment of the sequence. In this study, the sequencing strategy of first come first service (FCFS) method combined with constraint position shifts (CPSs) is adopted.

Assumptions:

(1) The weather in the TMA is clear.

(2) There are no special conditions of arrival flights such as diversion or alternate landing.

(3) The influence of departure flights on arrival flights in the TMA can be neglected.

2.2 Objective function

With the development of civil aviation, flights has increased rapidly, which leads to the frequent delays of arrival flights in TMAs. This paper aims to minimize arrival flight delays and increase runway capacity to improve the efficiency of TMAs

$$H = \mathrm{Min}\{\alpha D + \beta T\} \tag{1}$$

$$D = \frac{1}{n}\sum_{i=1}^{n}(\mathrm{STA}_i^L - \mathrm{ETA}_i^L) \tag{2}$$

$$T = \frac{m}{n}\mathrm{Max}(O_1, O_2, \cdots, O_m) \tag{3}$$

where STA_i^L represents the actual landing time of the arrival flight i; ETA_i^L is the expected landing time of the arrival flight, which is given by the flight schedule; O_i the runway occupancy time; D the average delay of all arrival flights; T the average landing separation of the arrival flights, m the number of runways; n the number of arrival flights; H the objective function; and α and β are the self-defined parameters set to 0.5 temporarily.

2.3 Constraints

(1) Constraints on safety separation

The safe operation of arrival flights in TMAs has always been the bottom line of all studies. Air traffic controllers usually adopt the method of maintaining vertical and horizontal separations between flights to ensure flight safety. Since the flights flying on the same sequencing leg have the same altitude, and the altitude change restrictions on the linking segments of the two PMSs are relatively stricter, this paper only needs to consider the horizontal separation, that is, the radar separation. Therefore, $S_{ij} > D_{ij}$. The radar separation D_{ij} in most TMAs is 10 km.

(2) Constraint on maximum position shift

For the PMS, the flight can turn and fly straight to the merge point at any position on the sequencing leg. So compared with the ordinary arrival procedure, the sequence of arrival flights is allowed to have a larger change. However, excessive flight position shift may cause additional workload for controllers, also undermine the fairness. In view of the above reasons, the maximum number of position shift of arrival flights in the PMS is set to 5.

2.4 Simulated annealing algorithm

The simulated annealing algorithm can quickly search for an approximate optimal solution when the solution space is large, and it is a kind of heuristic algorithm. In addition, in the simulated annealing algorithm, the solution generation is random to resist the interference of external unstable factors. For flight sequencing in TMAs, the amount of data is large, and the simulated annealing algorithm can have a shorter running time. Therefore, we used the simulated annealing algorithm to solve the sequencing problem in PMSs.

For the sequencing of arrival flights, all the different particle states inside the solid correspond to all possible sequences of the arrival flights. At a certain temperature, the value of the objective function of the flight sequence corresponds to the energy of the solid particles in the current state, which represents the degree of conformity to the objective function. The algorithm process is as follows:

Step 1 Set a sufficiently large temperature T, and determine the initial flight landing sequence K. Then set the temperature attenuation coefficient, the termination temperature T_e, and the number of iterations of the inner algorithm. For the initial flight landing sequence, calculate the value under the objective function and record it as $Z(K)$.

Step 2 Randomly generate a new flight landing sequence K' and check whether it meets the constraints. If the constraint conditions are met, calculate its objective function value, and record it as $Z(K')$.

Step 3 Calculate the difference of the objective function between the new and the old solutions. If $Z(K') < Z(K)$, the new arrival flight sequence is more suitable for the requirements of the objective function, and the new flight sequence K' becomes the latest solution. If $Z(K') > Z(K)$, accept the new solution with a certain probability, which is related to current temperature. The probability at the tth iteration is expressed as $p_t = \exp(-\Delta Z/\alpha^T)$, and then a random number on $[0,1]$ is generated. If $p_t >$ rand, accept K' as a new solution, and make $K = K'$, otherwises the current solution remains unchanged.

Step 4 Repeat steps 2 and 3 until the number of iterations meets the requirements, and the current solution is regarded as the local optimal solution.

Step 5 If $T < T_e$, the iteration is terminated, and the current solution is the global optimal solution; if $T \geqslant T_e$, the temperature changes: $T = \alpha^t T$, and reset the number of inner iterations. Then repeat steps 2, 3 and 4.

3 Examples and Anslysis

3.1 Data preparation

Guangzhou Baiyun International Airport is a 4F civil airport. In 2020, even when the global civil aviation industry was severely impacted by the COVID-19 epidemic, passengers that have transited in Guangzhou Baiyun International Airport reached 43.768 1 ,ranking the first worldwide[13]. Baiyun Airport has three runways: 01/19, 02L/20R and 02R/20L. 02R is the main landing runway for arrival flights, so this paper selects approach traffic on runway 02R.

In order to better reflect the potential advantages of serial PMSs compared with a single PMS in alleviating delays, increasing TMA capacity and to verify the applicability of serial PMSs under high traffic loads, 81 flights during the busy period from 18:00 to 20:00 on the typical day are selected.

There are five entry points in the Guangzhou TMAs: ATAGA, IGONO, P270, IDUMA, GYA and P71. Among them, P71 needs to obtain ATC permission to fly, and is not used in actual work. So this paper does not consider it. ATAGA, IGONO, P270, IDUMA and GYA converge traffic flows arriving from the northeast, the southeast, and the west. The traffic flows of the arrival point of ATAGA is 20.92%, GYA 35.11%, IGONO 32.45%, P270 10.99%, and IDUMA 0.53%. It can be seen that the northeast direction accounts for more than half of the approaching traffic flows, the busy direction of the TMA. The traffic flow in the northeast direction of Guangzhou TMA is significantly more than that in other directions. Therefore, this TMA is suitable for designing serial PMSs.

As shown in Fig.3, the red line is the Guangzhou TMA, and the green line is the original single PMS of Baiyun Airport. Since it is located at the northeast boundary of the Guangzhou TMA, the length of the sequencing leg is 50 km, and the radius lengths of the outer side and the inner side are 65 km and 55 km, respectively. The large distribution area can accommodate more arrival flights. This can facilitate and integrate arrival traffic from the northeast, and benefit the initial adjustment of the order of flight in the busy direction. In this paper, on the basis of reserving the original PMS, a PMS in series with the original single PMS is designed near the final of the runway.

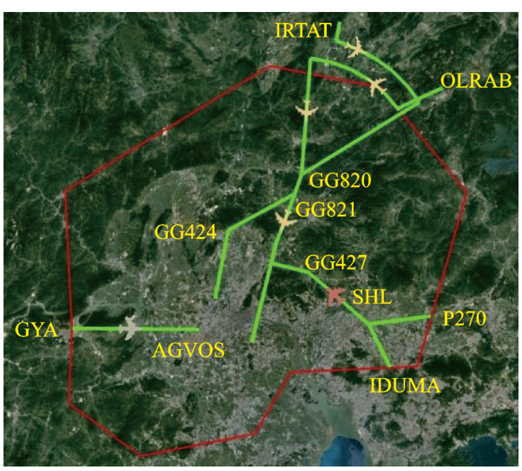

Fig.3 Existing PMSs of Guangzhou TMA

3.2 Design of serial PMSs

Under the premise of the requirements of the PMS structure design, this paper adds a PMS to the southwest side of the TMA on the basis of the original PMS to form a serial PMSs. According to the original standard arrival procedures, the serial PMSs consider the distribution of obstacles and the influence of the existing procedure. As shown in Fig.4, the arrival flights in the northeast direction first go through the PMS in the northeast direction for initial sequencing. After receiving the "direct to" instruction, the flights fly to the waypoint GG820 and then fly along the linking segment of the two PMSs. Finally, the flights enter the outer sequencing leg of the second PMS, and perform a secondary sequence with the flight from the west and the southeast of the TMA to determine the final approach sequence. Since there are fewer flights from the west and the southeast, only one sequence adjustment is required. After flying along standard arrival procedures, the flights enter the inner sequencing leg of the PMS located near the final.

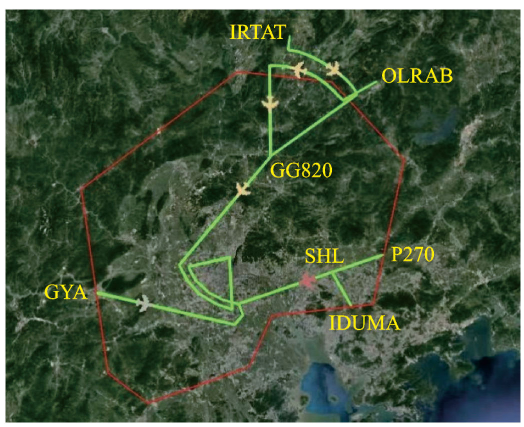

Fig.4 Serial PMSs of Guangzhou TMA

In the newly added PMS, the merge point is located at 23°13′48.00" N and 113°8′39.00" E. There are two sequencing legs, which are separated horizontally and vertically. In the horizontal direction, because the flow of the northeast arrival flights is roughly the same as the west and southeast arrival flights, the outer sequencing leg with a radius of 31 km is used for the secondary sequencing of the arrival flights in the northeast direction after the initial sequencing. The length of each segment on the outer side is 10 km, and the total length is 40 km. In the vertical direction, the inner side is 300 m higher than the outer side to ensure that the flights on different sequencing legs always have enough vertical separation. Finally, given the altitude requirements of the final approach, the descent gradient requirements of the flight approach, and the altitude of the original arrival procedure, the design altitude is as follows: The height of the merge point is 900 m; the height of the outer sequencing leg is 1 500 m; and the height of the inner sequencing leg is 1 800 m.

3.3 Comparative experiment on operating benefits of traditional PMS and serial PMSs

The key information such as the flight segment data of the single PMS, serial PMSs, etc., and the flight data during peak hours are substituted into the theoretical model in Section 2. Then the simulated annealing algorithm is used for calculation. The initial temperature for heating is set as 1×10^{10} ℃, the final temperature for heating is set as 1 ℃, the cooling rate is set as 0.9 and number of iterations at the same temperature is set as 50.

Fig.5 (a, b) shows the iterative process of the single PMS and the serial PMSs using the simulated annealing algorithm. It can be seen that the algorithm has good convergence. For a single PMS, when the number of iterations is about 20, the optimal solution has tended to converge. For the serial PMSs, when the number of iterations is about 25, the optimal solution tends to converge.

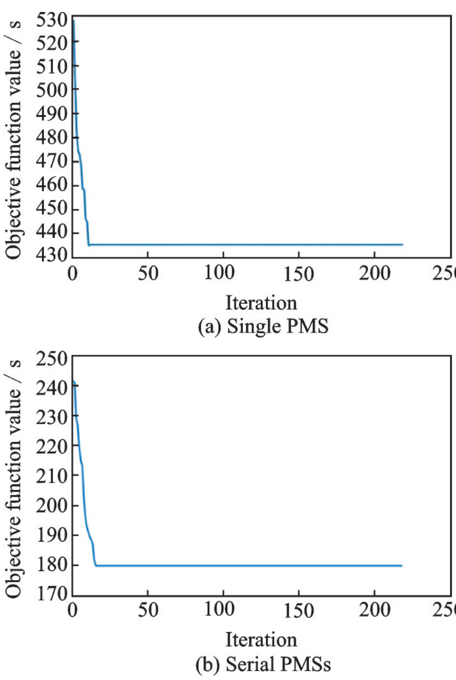

Fig.5 Optimization of operational benefits of arrival flights in PMS by SA

The serial PMSs has significant advantages in reducing delays. Compared with the single PMS, the objective function value of the serial PMSs is reduced by 1.6 min, that is, it reduces the objective function value of the single PMS by 33.3%. The average delay value is reduced by 3.1 min compared with the single PMS, that is, it reduced the average delay time of a single PMS by 38.8%.

The reason is that the serial PMSs can make the adjustment of the flight sequence more deeply, so that it can iteratively obtain the flight sequence that is more suitable for the objective function value. As shown in Fig.6, in the single PMS, 71.1% of the flight orders are not exchanged, while in the serial PMSs, the flights without order exchange accounts for only 23.5%. It can be seen that the use of the serial PMSs can greatly change the landing order of flights, that is, the flight sequence adjustment in the serial PMSs is more flexible.

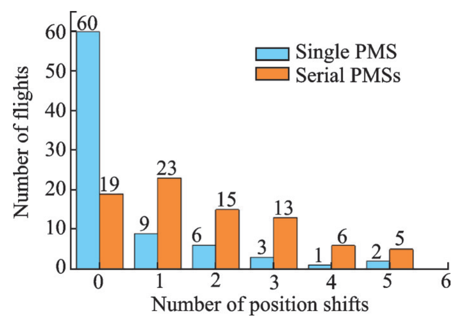

Fig.6 Comparison of flight sequence adjustment between single PMS and serial PMSs

In order to further demonstrate the applicability of the serial PMSs under different traffic flows, this paper reduces the number of arrival flights during the peak hours to 60, 70, and increases to 90 and 100 according to the distribution of arrival flight flows. Fig.7(a, b) shows the average delay time and the objective function value of the single PMS and the serial PMSs under different number of flights. It can be seen from Fig.7 that no matter it is the average delay time or the value of the objective function, the operational efficiency of the serial PMSs is higher than that of the single PMS. When there are 100 arrival flights, the difference between the objective function value and the average delay value of the single PMS and the serial PMSs is 22.8 s and 42 s, respectively. Compared with the 81 arrival flights in a typical day, the difference has increased by 24.6% and 23.6%, respectively. The data show that the serial PMSs have more advantages in the case of high traffic load, and with the growth of flight traffic, the advantages of the serial PMSs become more obvious.

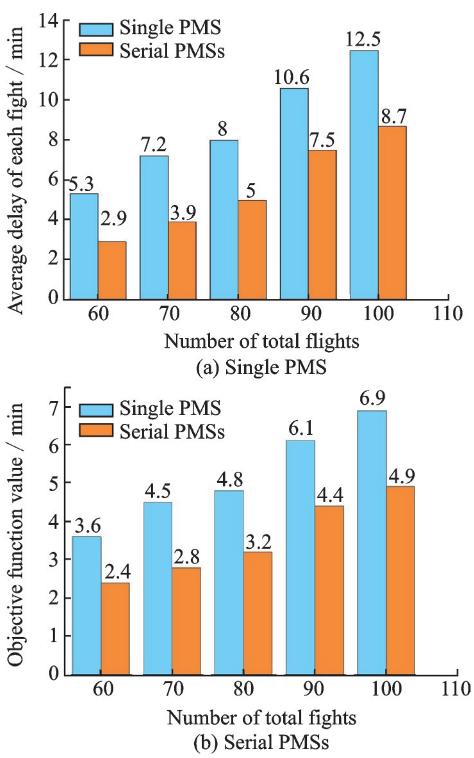

Fig.7 Comparison of operational benefits of single PMS and serial PMSs

3.4 Impact of custom parameters

In order to explore the impact of the custom parameters in the objective function on the output results, this paper resets the values of the custom parameters α as 0.1, 0.5, and 0.9; and β is 0.9, 0.5, and 0.1. The experimental results are shown in Table 1.

It can be seen from Table 1 that as the value increases, the influence of the average delay value on the final objective function value increases, and the average delay value gradually decreases. Similarly, as β decreases, the influence of the average landing separation on the objective function value decreases, and the average landing separation gradually increases, that is, the runway throughput gradually decreases. Therefore, when minimizing delay is the main goal, α can be increased appropriately. When minimizing the landing separation and maximizing runway throughput are the main goals, β can be increased appropriately. But no matter how the value of α and β changes, it always needs to satisfy the constraint that the sum of the two is equal to 1.

Table 1 Effect of different parameter settings for the objective function

Comparison of the content	$\alpha=0.1$	$\alpha=0.5$	$\alpha=0.9$
	$\beta=0.9$	$\beta=0.5$	$\beta=0.1$
Average landing separation/s	89.74	90.29	90.50
Average delay/s	510.56	471.99	469.92
Objective function value/s	131.829 4	281.144 8	431.975 8

4 Conclusions

In order to improve the operational benefits of arrival flights in TMAs, this paper studies the applicability of serial PMSs, a brand-new flight procedure. The conclusions are as follows:

(1) In the process of PMS design, we put the first PMS in the extended TMA or near the boundary of TMAs, which allows controllers adjust the aircraft sequence in advance. we put the last PMS near the runway, which allows controllers adjust the aircraft sequence accurately. These meet operational requirements of TMAs.

(2) The serial PMSs has significant advantages in reducing delays and increasing runway throughput because it can adjust the flight sequence more deeply.

(3) The serial PMSs can show their advantages in high traffic loads.With the growth of flight traffic, the advantage of serial PMSs will become increasingly obvious.

The serial PMSs can significantly improve the operational benefits of arrival flights in TMAs, thus making a meaningful exploration on how to further utilize the airspace resources in TMAs and improve the operational benefits of arrival flights. It is conducive to promote the implementation and application of serial PMSs in China.

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Author contributions Ms. **XU Can** designed the study, complied the models, conducted the analysis, interpreted the results and wrote the manuscript. Ms. **WANG Xunuo** contributed to data and model components for the sequencing model. Prof. **TIAN Yong** contributed to data for the analysis of Baiyun airport. Dr. **WANG Zhan** contributed to the discussion and background of the study. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Prodnction Editor: ZHANG Bei)

串联点融合系统对进场航班运行效益的影响

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摘要：为了缓解终端区内的航班拥堵，开发一种有效的进场航班排序方法具有重要意义。构建基于串联点融合系统（Point merge system，PMS）的进场排序模型，以提高到达航班的运营效益。将先到先服务与约束位置交换相结合，用作排序策略。通过模拟退火算法求解，结果表明，使用串联PMS的进场航班排序在减少延误和提高跑道吞吐量方面具有显著优势，特别是在高交通负荷的情况下，这有利于促进串联PMS在中国的实施和应用。

关键词：串联点融合系统；终端区；进场航班；运行效益